Bringing a Star to Earth

Summary

Fusion energy is arguably one of the most important and rewarding research challenges of the 21st Century. The ultimate objective of a safe, economic power source free of greenhouse gases, using widely available fuels, and with no long-lasting hazardous by-products has motivated scientists, politicians, and citizens alike.

A fusion engine powers every star in the known universe. The huge gravitational forces within stars allow them to confine the reacting fuel elements in a plasma wherein the lighter elements fuse together to make heavier elements and energy. The challenge of bringing the power of the stars down to earth is considerable, but scientists have already made enormous progress in this endeavor.

The two principal approaches for confining the fusion fuel[1] on earth are magnetic and inertial. Magnetic fusion relies on magnetic forces to confine the charged particles of the hot plasma fuel for sustained periods of fusion energy production. Inertial fusion relies on intense lasers or particle beams to compress a pellet of fuel rapidly to the point where fusion occurs; yielding a burst of energy that would be repeated to produce the sustained energy production. In both cases the intellectual challenge of describing the dynamics of the confined hot plasma with its turbulent mix of charged particles, which are both subject to magnetic and electric fields and are required to internally generate these fields as well, has stimulated the rapid development of plasma physics. The behavior of these plasmas requires an understanding of fluid mechanics, magnetohydrodynamics, kinetic theory, nonlinear dynamics and leading-edge computer simulation. Developments in fusion and plasma science have directly contributed to neighboring disciplines such as astrophysics, atomic physics, and communication sciences. There have also been many technology spinoffs in areas such as plasma processing, waste disposal, lighting, and space thrusters.

Over the last decade, there has been extraordinary progress in 1) the ability to model complex plasmas with state of the art computer systems employing refined theoretical understanding, and 2) the ability to measure with incredible detail the internal characteristics of plasmas at near-reactor conditions (i.e., temperatures 10 times the surface of the sun). With these coupled advances in simulation and instrumentation has come a vast improvement in our ability to design and build the machines of the future.

Many inventive configurations of magnetic fields have been proposed for confining the plasma fuel as it is heated to the conditions necessary for fusion. The most successful have been toroidal systems, especially the Russian-originated tokamak that is the primary focus of world research. The fusion power produced in these machines has improved by six orders of magnitude (from a few watts to megawatts) over the past two decades.

Twice in the past decade the world fusion program has held the flickering flame of fusion energy in its collective hands—first, during experiments producing 10 Megawatts of power

[1] Deuterium and tritium, two isotopes of hydrogen are the easiest elements to fuse together. The net product of this fusion is helium (an inert gas) and a neutron that carries most of the energy—the deuterium in a gallon of seawater is equivalent to 300 gallons of gasoline.

and lasting about a second on the Tokamak Fusion Test Reactor at Princeton Plasma Physic Laboratory, and then subsequently for even longer pulses and higher power on the larger Joint European Tokamak near Oxford, U.K. In each case scientists have analyzed and modeled the results to the point where the limitations are clearly understood and scaling to the next step burning plasma experiment is well in hand.

World fusion scientists have designed several burning plasma experiments, in which the actual fusion energy process dominates the power input into the plasma. The International Thermo-nuclear Experimental Reactor (ITER) is the result of many years of collaborative effort (including the U.S. through 1998) and incorporates the world's collective understanding of how best to construct such an experiment. Canada, Europe, and Japan have offered to host the device and negotiations are under way. The cost of the ITER facility has been recently reduced by almost a factor of two (following directions the U.S. had been recommending earlier) and recent physics developments have also increased confidence that the project will meet its goals. The U.S., as a founding member, has been invited to join the ITER negotiations and is considering whether to do so.

A second burning plasma option would be based on a tokamak with copper coils, such as FIRE, a U.S. design that would be smaller and cost less than ITER. FIRE would also have a much shorter pulse length than ITER, reducing its capability to explore some of the scientific and technological issues associated with burning plasma. A key programmatic issue is that an integrating fusion research facility like ITER would be required between FIRE and a fusion demonstration plant. ITER is expected to be the last major step between today's experiments and a demonstration plant, although much work needs to be done in parallel with ITER on the development of materials for fusion power and in the continued pursuit of better, possibly more cost-efficient confinement methods.

If the U.S. chooses to join ITER, it will be imperative to continue and strengthen the basic elements that have provided the insights leading to the improved ITER design in the first place. The core U.S. strengths in theory and modeling, diagnostics, advanced and innovative concepts, and plasma and fusion technologies will be needed to ensure the success of ITER and the pathway to fusion energy.

Just as the magnetic fusion energy program can leverage off of worldwide fusion research and has been closely coupled to the broader international fusion programs for mutual benefit, the U.S. fusion energy efforts can also benefit from the large U.S. defense program investments in inertial fusion of pellet targets using lasers. The National Ignition Facility (NIF) is many times larger than any previous inertial confinement device. It presents a unique opportunity to produce information on target compression that could be used in energy-oriented studies using ion beams or newer kinds of lasers to compress the pellets for energy purposes. A modest investment on the energy aspects of inertial fusion could produce substantial dividends, given the coming availability of the NIF that starts operation in 2004.

"I think fusion is going to be an important energy technology for the future and we need to be working toward that end." — John Marburger, Presidential Science Advisor on NPR (January 18, 2002)

For further information on this subject contact:
Dr. Anne Davies, Director
Office Fusion Energy Sciences
301-903-4941
anne.davies@science.doe.gov